Development of texture and critical currents in 3 micron thick YBCO films on RABITS substrates.

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DOE Peer Review 2006

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Outline

$$J_c = \boxed{\text{Structure}} \times \text{Pinning}$$

- BNL expertise: applied thermodynamics of structure formation
- BNL approach: raising J_c though the structure improvement

- Structural factors limiting performance of thick YBCO films.
- Analysis of structure-forming events.
- Thermodynamics of nucleation of technical buffers.
- Plans for 2007 and conclusion.

2006 goals

- Study of the growth of YBCO thick films on substrates with different buffer layers, emphasis on substrates manufactured on large scale .

- Further work on understanding factors controlling orientation of YBCO nuclei and YBCO grains.

- Additional thrust towards better characterization of structure and crystallographic order of thick YBCO layers.

Project integration:

- Study of flux pinning in 3 μm and 4 μm films, L. Civale and B. Maiorov, LANL. Growth on IBAD substrates, V. Matias.

- TEM, SEM and Raman microscopy of isolated YBCO nuclei, V. Maroni, D. Miller, ANL.

- Joint studies of nucleation using various substrates and precursor layers, X.Li, AMSC.

- Assistance to Superpower in set-up of composition analysis system.

Two step of BaF_2 process:

1) Vacuum evaporation of Y, BaF_2 and Cu on buffered Ni-W tape.

2) Conversion:
Precursor(Y,BaF_2,Cu) + H_2O +O_2 = YBCO+HF↑

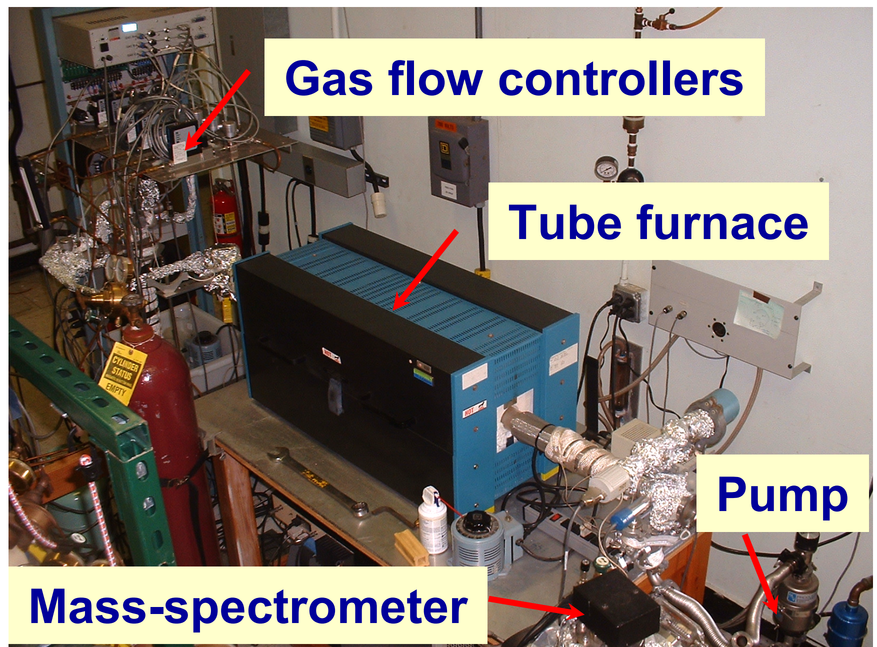
Processing conditions:

p(Total) = 21 Torr

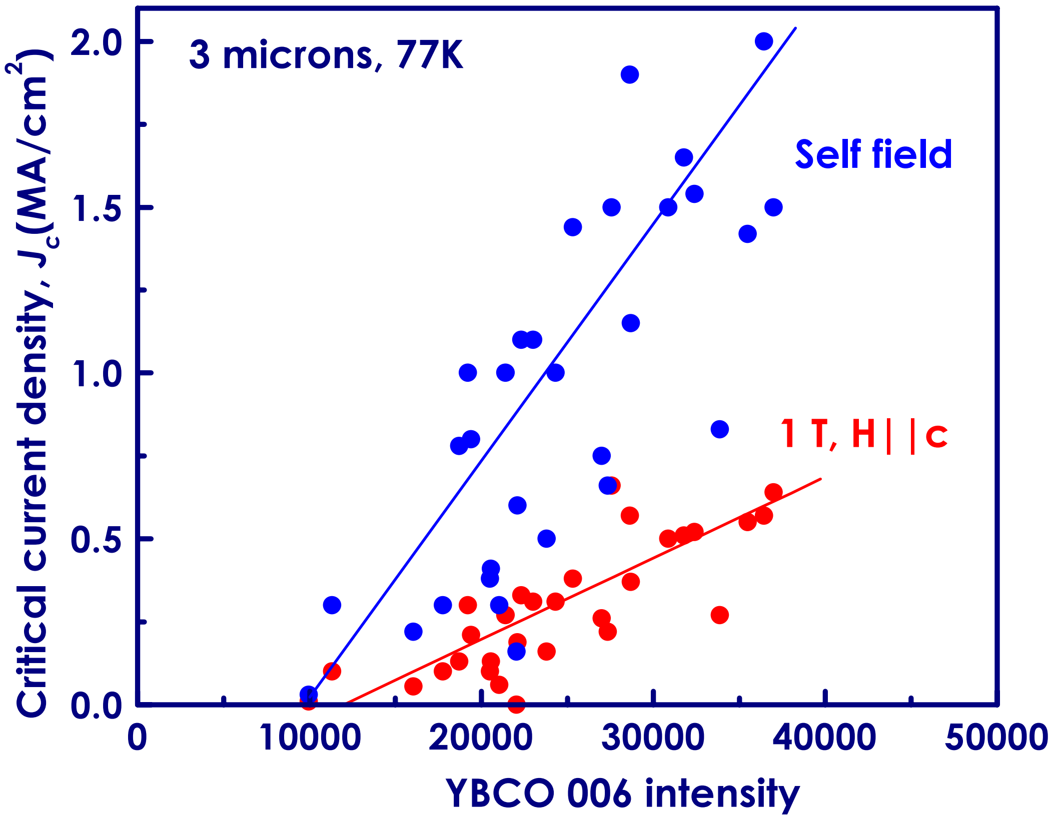
$p(H_2O)$ = 0.5 Torr

$p(O_2)$ = 50-300 mTorr.

T = 735 °C.



Summary of 2006: structure quality vs. J_c for 3 μm films on 4 cm AMSC tape.

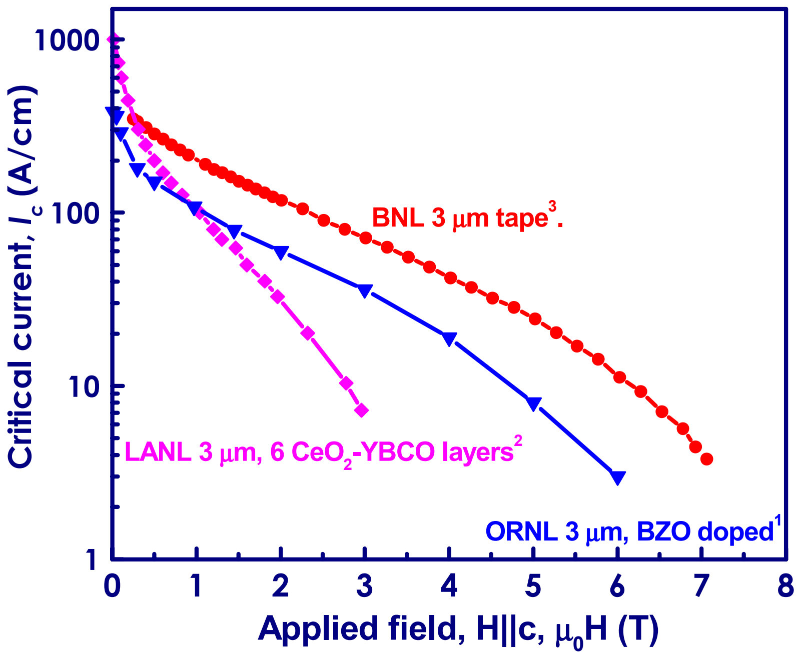


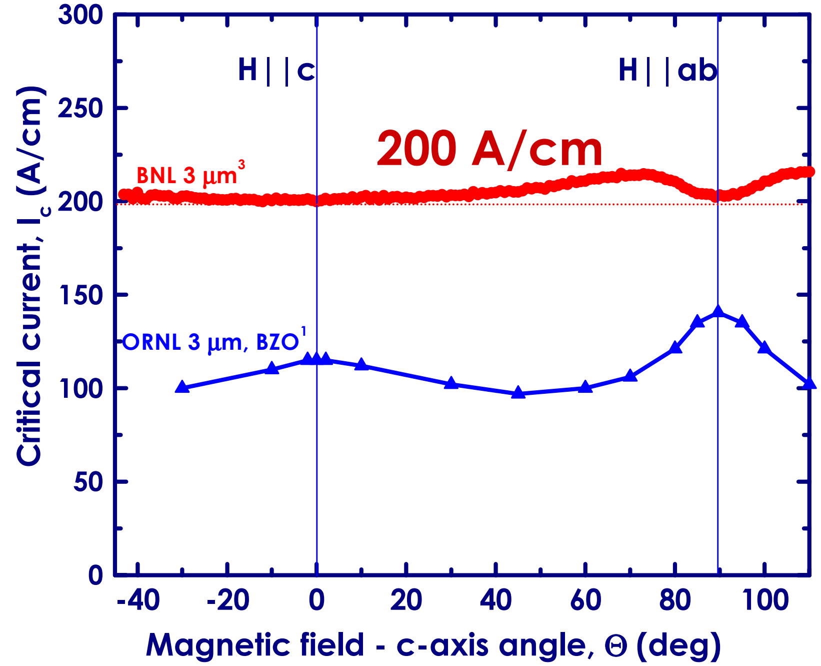
✓ J_c (0 T) = 1.9 MA/cm^2, J_c (1 T, H||c) = 0.66 MA/cm^2, T_c = 92.5K

✓ There is a lot of potential in structure improvement.

Performance of 3 μm films on AMSC tape in liquid nitrogen.

1 Tesla field





[1]PLD deposited YBCO with BZO columnar structures, S. Kang, et al. *Science*, 311, p. 1911 (2006).
[2]X. Jia, S. R. Foltyn, P. N. Arendt, and J. F. Smith, *Appl. Phys. Lett.*, 80, p. 1601, (2002).
[3]Transport J_c measurement by L. Civale and B. Maiorov, LANL.

✓ **BNL 3 μm sample exhibited very strong isotropic pinning, which was combined with high T_c.**

Benefits of BNL "improving structure" approach.

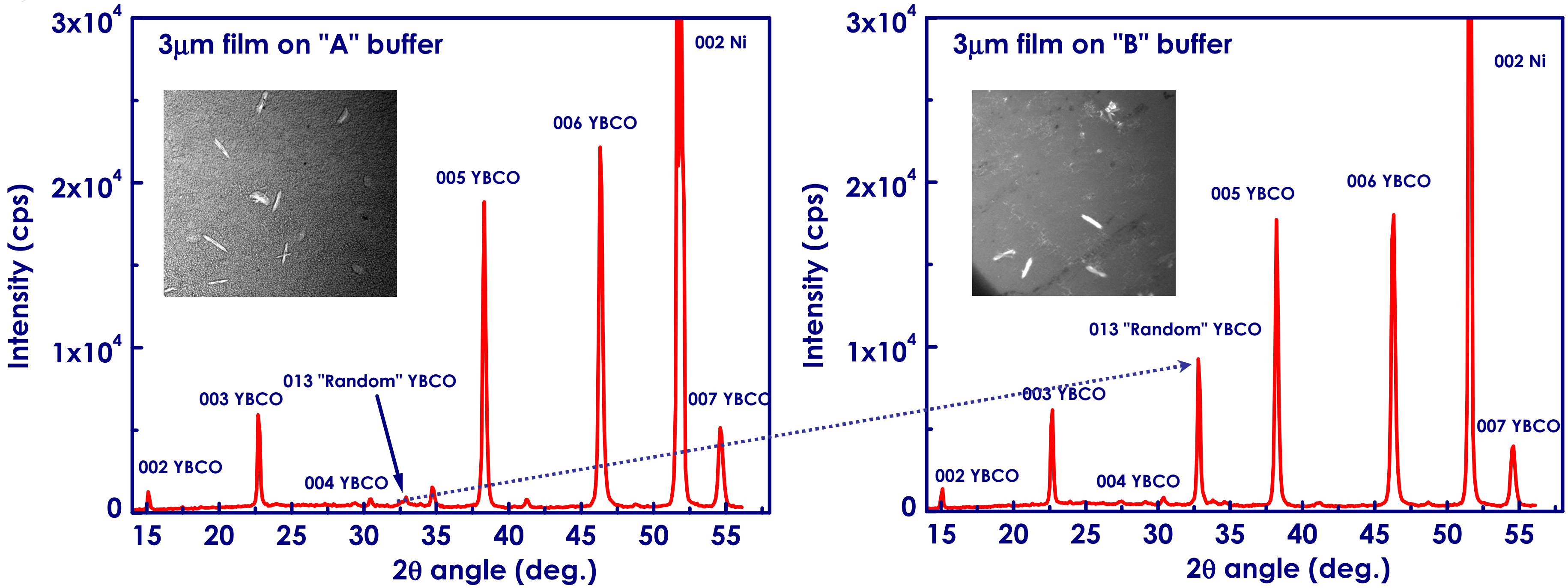
- By improving structure we do not degrade T_c! BNL 3 μm sample T_c = 92.5 K.

  For example, BZO columnar pins reduce T_c to 86.2 K.

- Isotropic J_c up to 3 Tesla field at 77 K.

- Excellent J_c retention in magnetic field, J_c reduces only by a factor of 3 in 1 T field at 77 K.

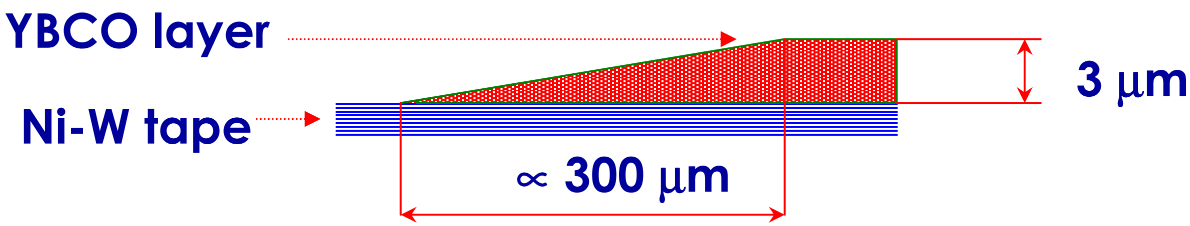
Understanding difference between buffers: 3 μm YBCO layers on buffers “A” and “B”.

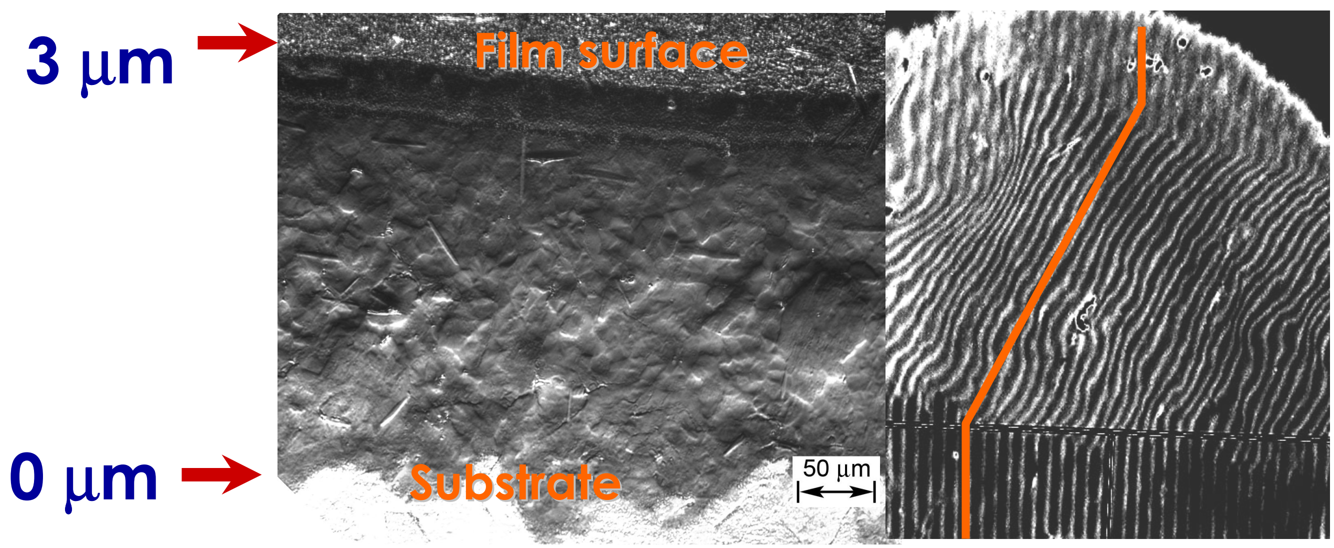


2005, buffer “A”, J_c = 1.1 MA/cm² **2006, buffer “B”, J_c = 0.4 MA/cm²**

✓ **(103) peak intensity does not correlate with density of visible randomly oriented grains.**

Low angle polishing of YBCO layer: optical cross-section of the YBCO layer.



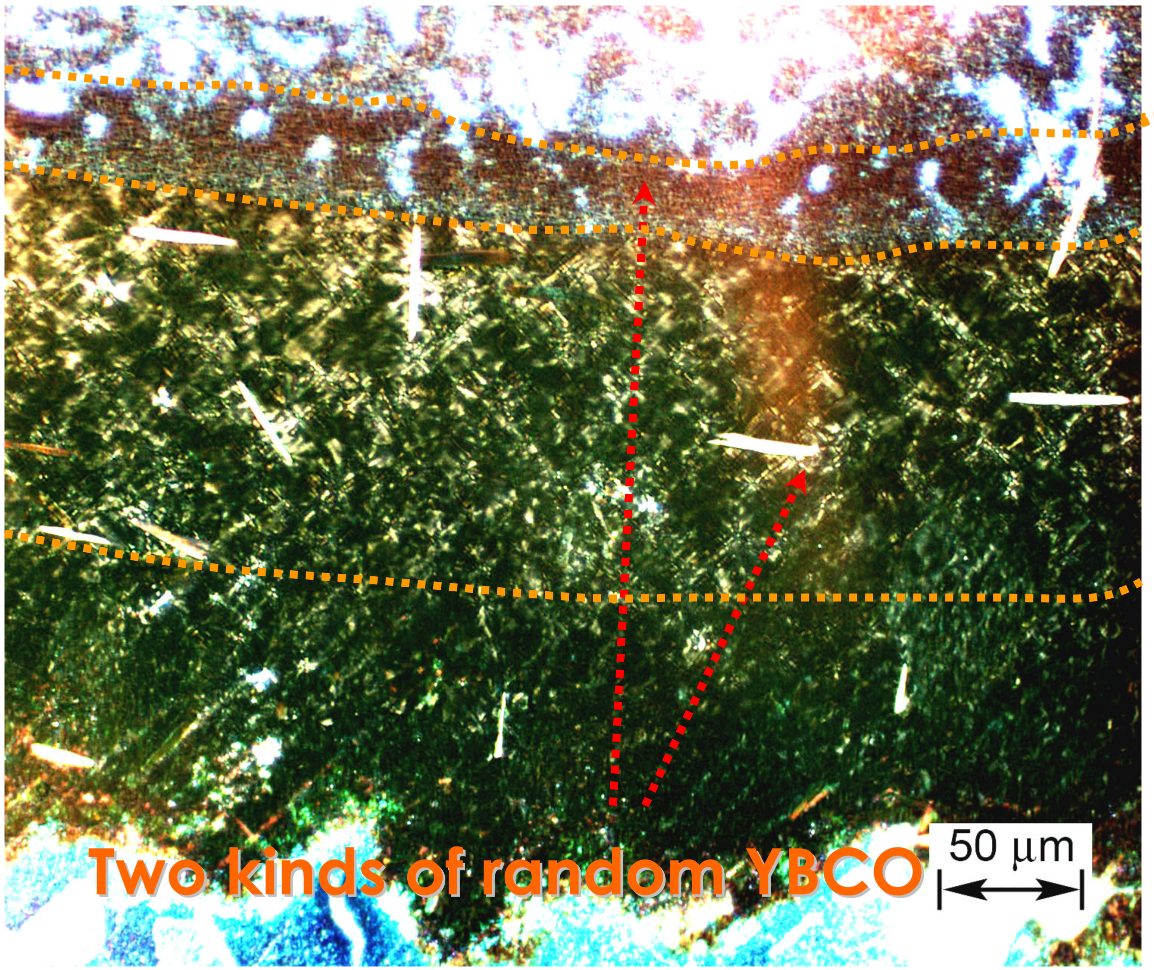


Optical contrast

Interference fringes (Na D line)

- ✓ We can linearly stretch 3 microns into 300 microns.
- ✓ It takes just 10 minutes per sample.

Typical structure of a 1 MA/cm^2 3 μm film: three layers (polarization contrast)



film surface

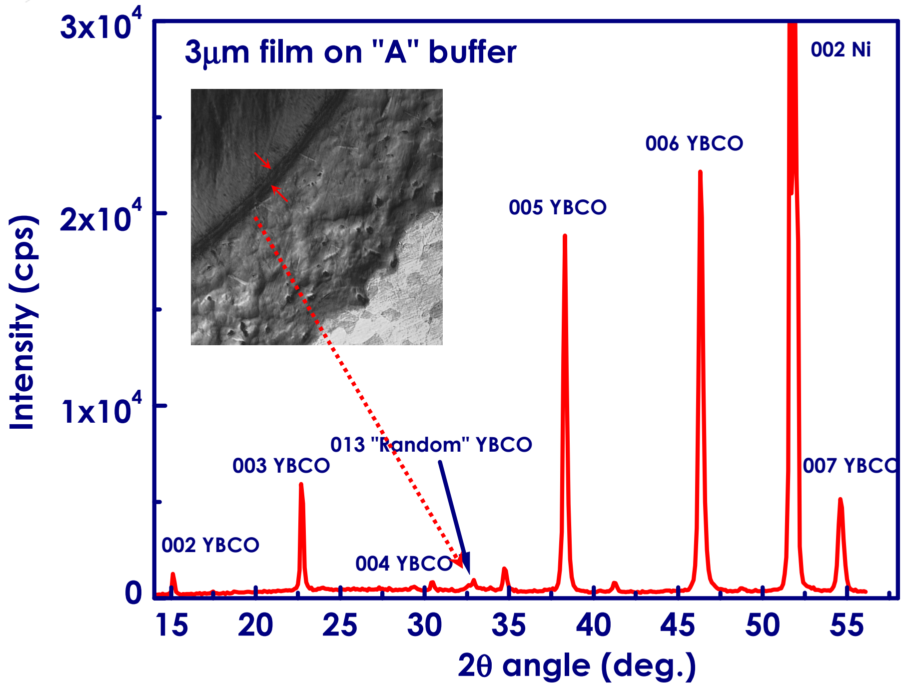
0.4 μm random YBCO

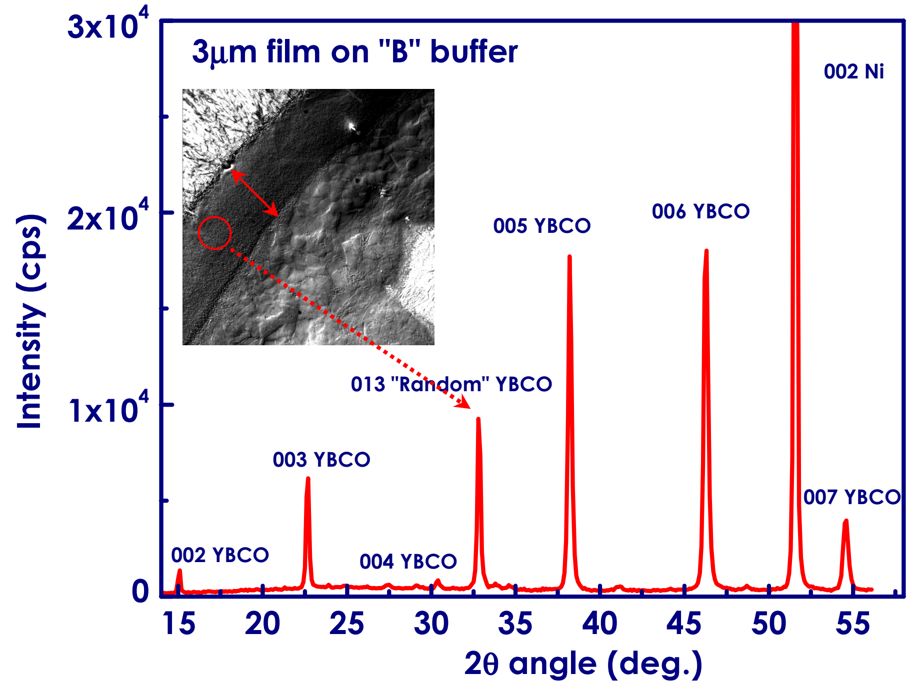
1.9 μm
c-oriented YBCO
laminar growth
well defined twins

0.7 μm
c-oriented YBCO
merged nuclei

substrate

Thickness of randomly oriented near-surface layer is buffer-dependent.



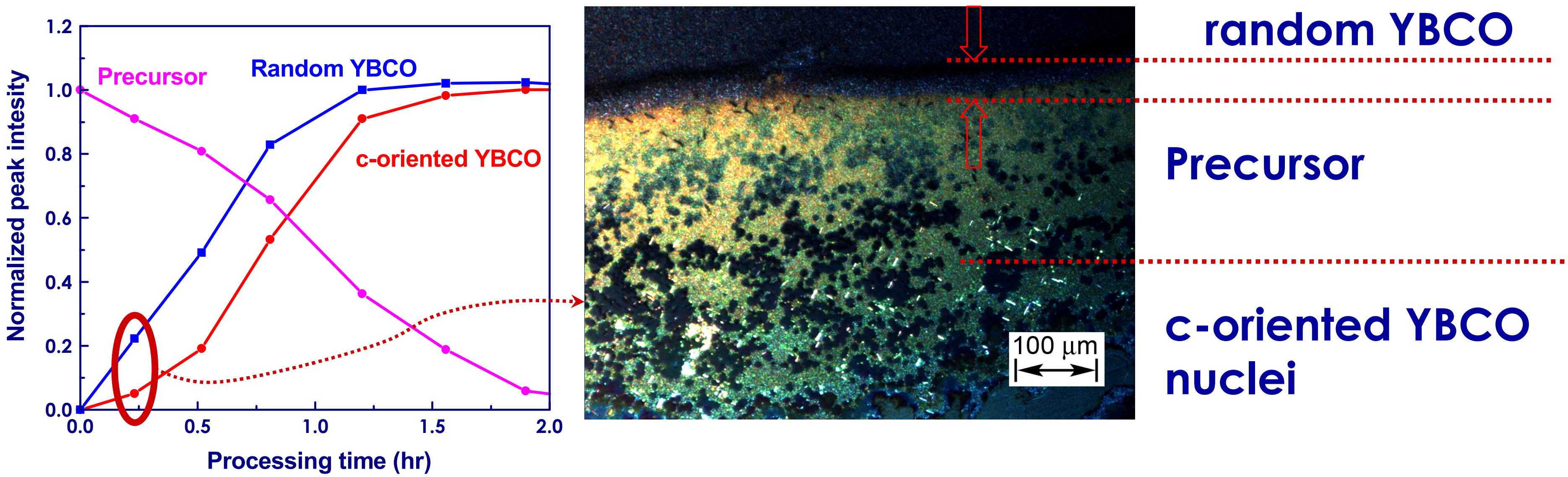


Buffer "A", J_c = 1.1 MA/cm^2
Near-surface layer = 0.2 μm

Buffer "B", J_c = 0.4 MA/cm^2
Near-surface layer = 1.3 μm

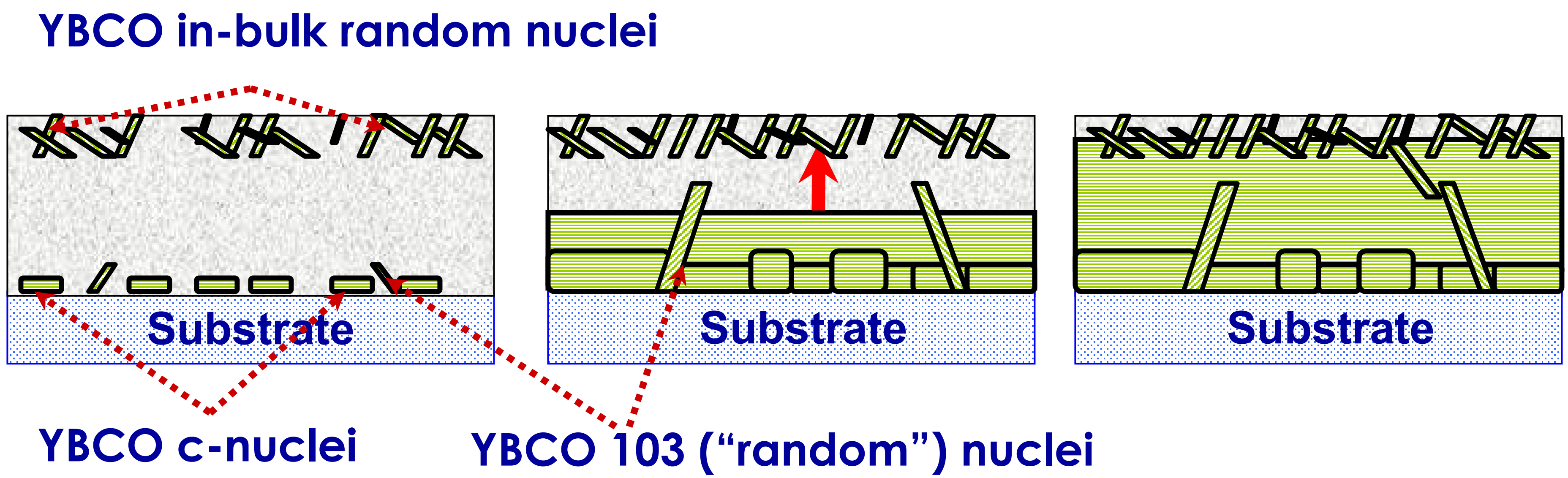
- ✓ **Buffer "B" had much thicker near-surface randomly oriented layer.**
- ✓ **To address this problem, we needed to modify our approach.**

Angle polish of a quenched sample, processed for 15 min (10% completion).



✓ **Randomly oriented near-surface layer develops at early stages of processing.**

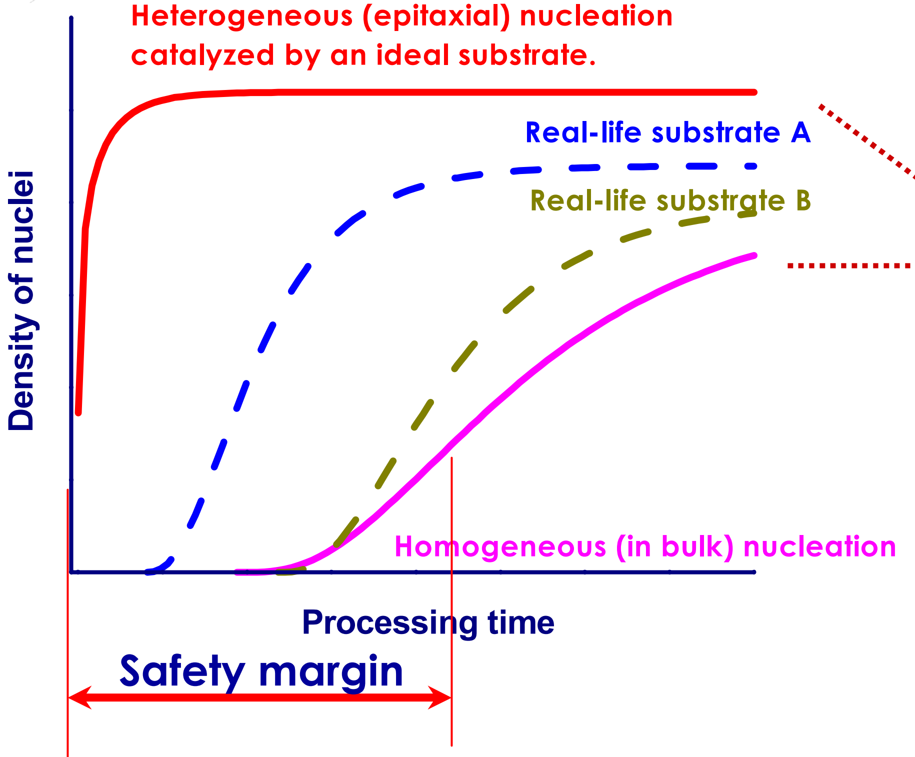
Layered structure of a thick film: competition of in-bulk and epitaxial nucleation.

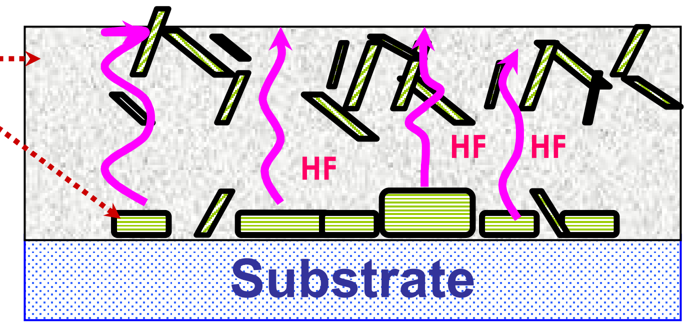


✓Competition between epitaxial nucleation of the substrate and random nucleation in the near-surface layer.

✓Why near-surface nucleation is thickness and substrate-dependent?

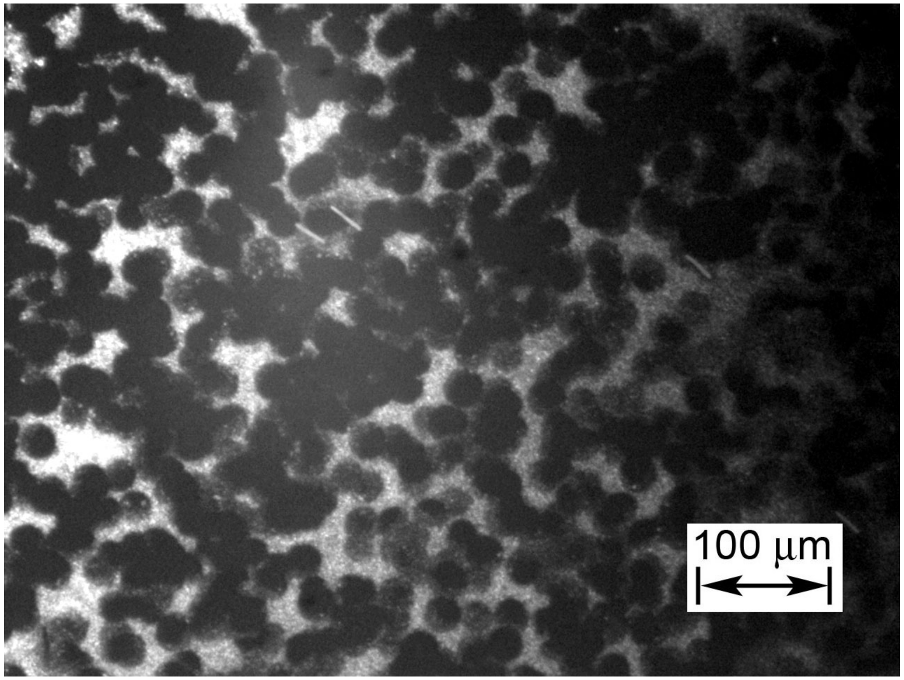
Epitaxial vs. homogeneous nucleation. Difference between ideal and real-life substrates.



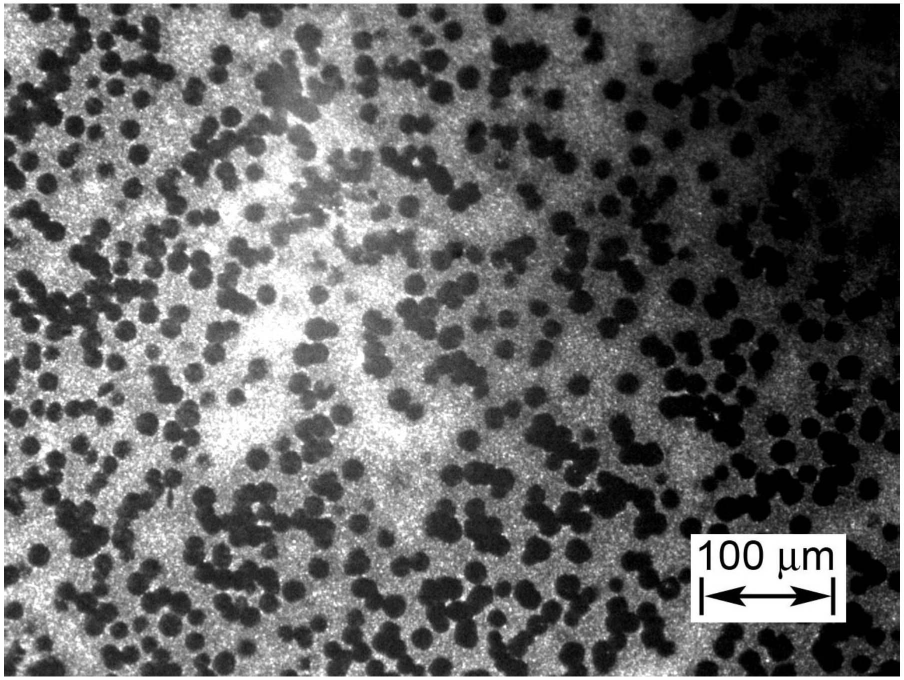


- ✓ For an ideal substrate, rate of epitaxial nucleation is much higher than homogeneous one. Large safety margin.
- ✓ Real-life substrates are not so effective catalysts and the safety margin may be very low, especially for thick films.

Nuclei distribution in buffers “A” and “B”. Planar polishing of quenched samples.



Buffer “A”

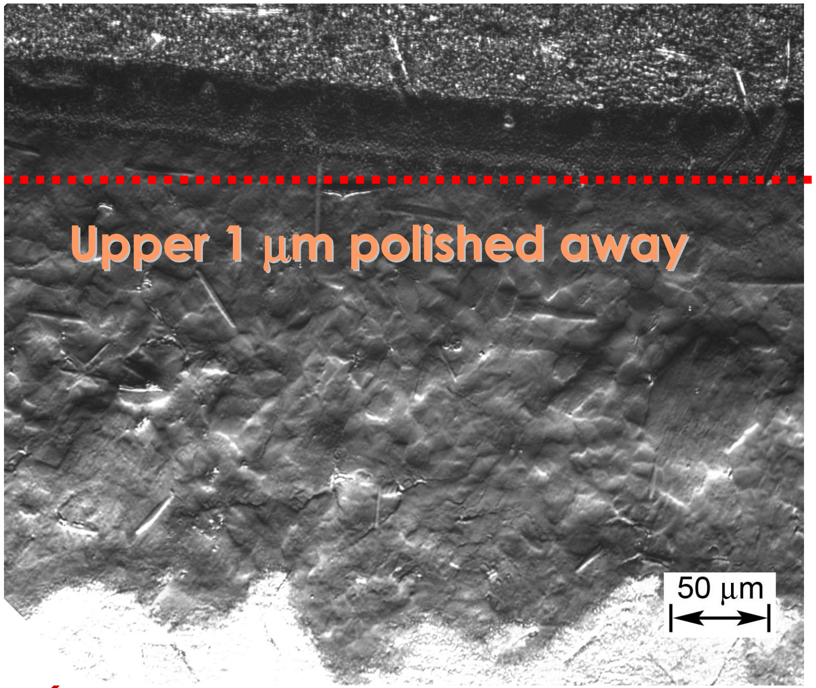


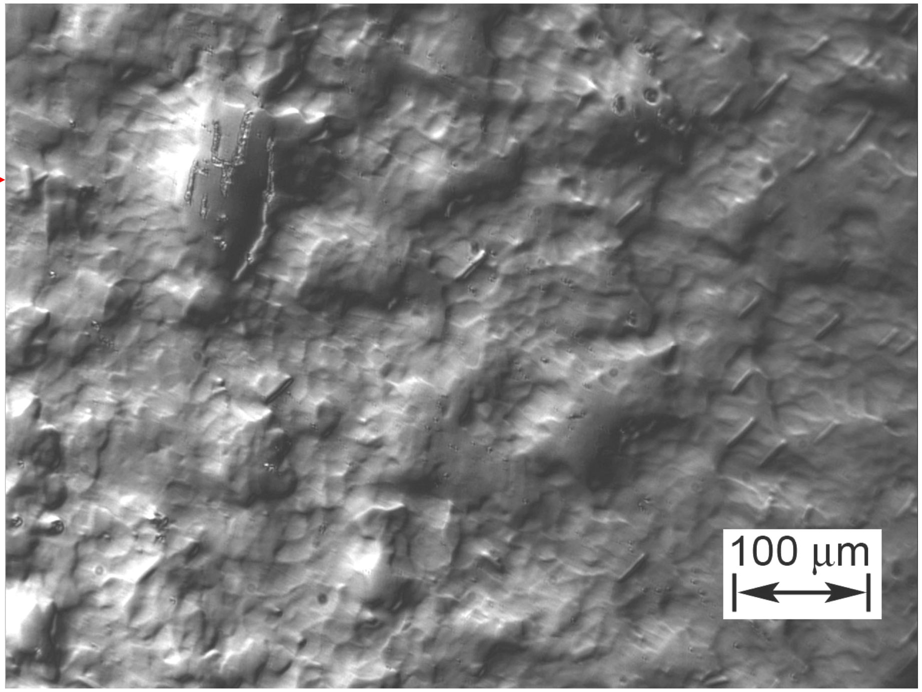
Buffer “B”

✓It takes more time for YBCO to nucleate on buffer “B”.

✓For buffer “B” we need lower supersaturation (low $P(O_2)$ and growth rate) to suppress near-surface random nucleation.

After minimization of the pre-surface nucleation granularity became the limiting factor.

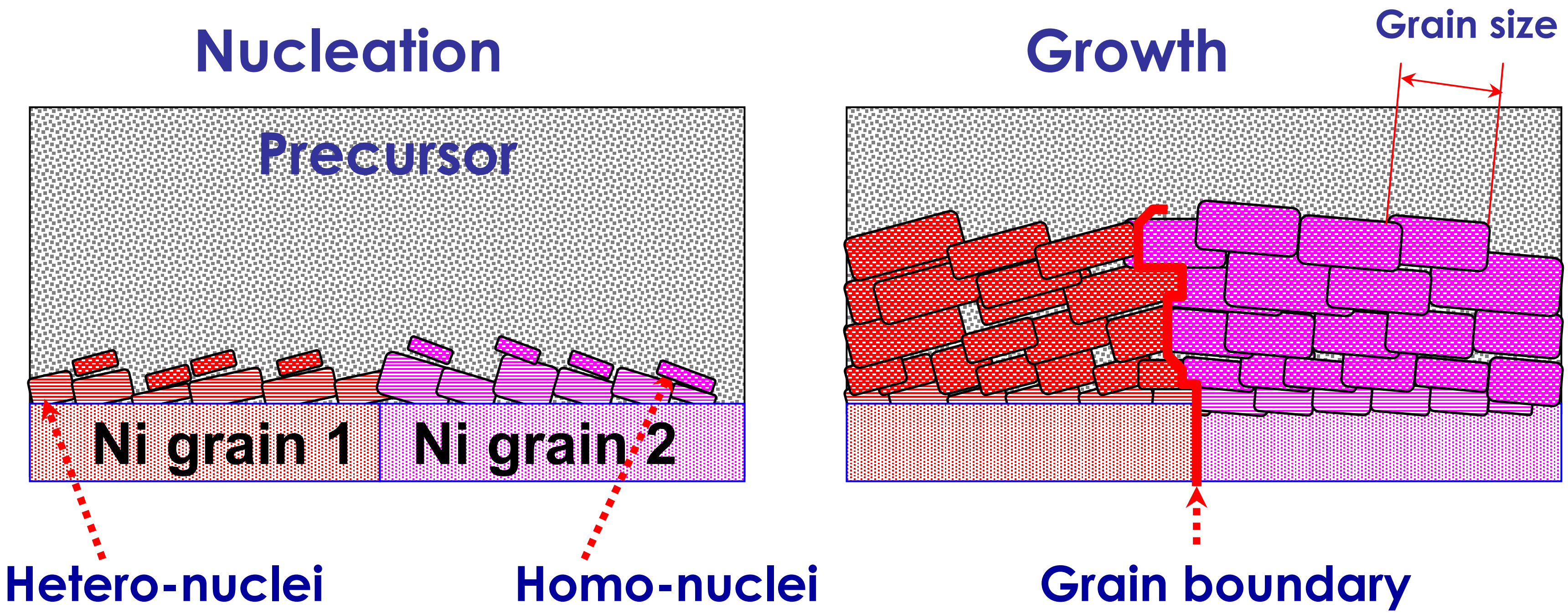




✓ We consider near-surface random layer thickness <0.3 μm acceptable.

✓ Granularity is persistent throughout c-axis oriented layer. To get J_c over 1 MA/cm^2 we need to make grains smaller than 10 μm.

Model of growth of c-axis oriented layer: possible origins of the granularity.

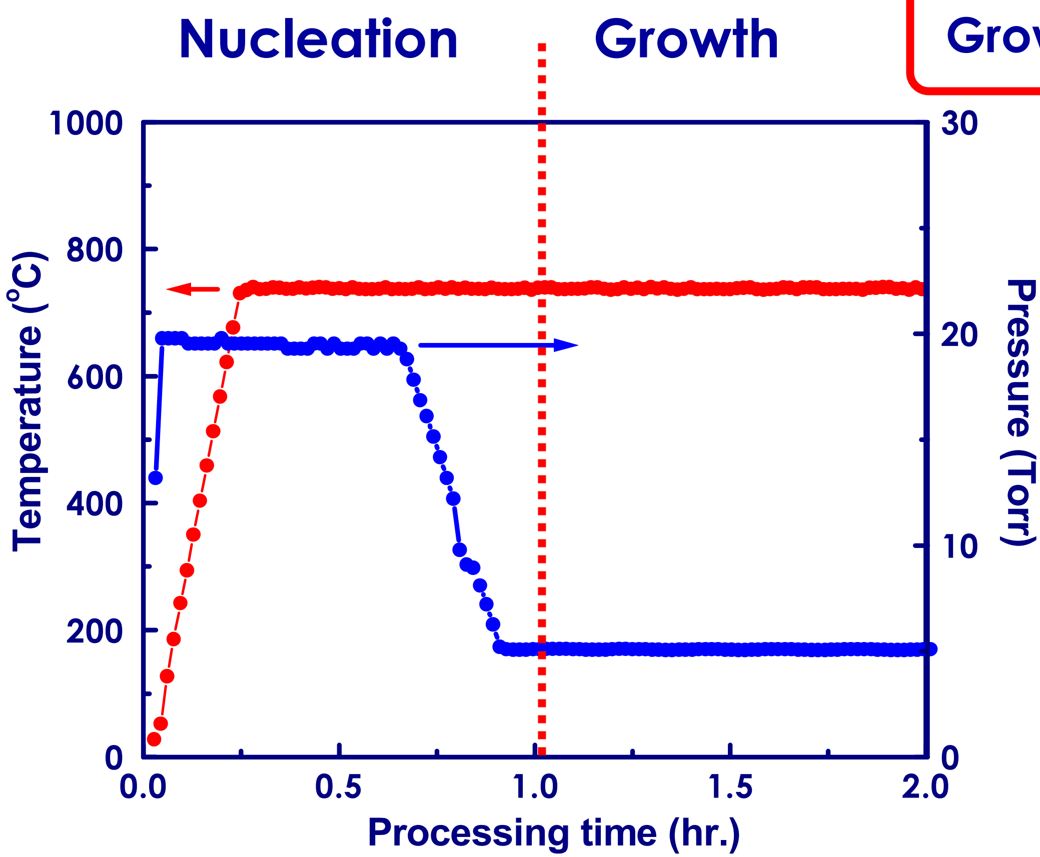


✓ After the nucleation stage the growth proceeds as series on nucleation-merging events.

✓ To reduce the grain size we need to increase rate of nucleation (speed up the growth).

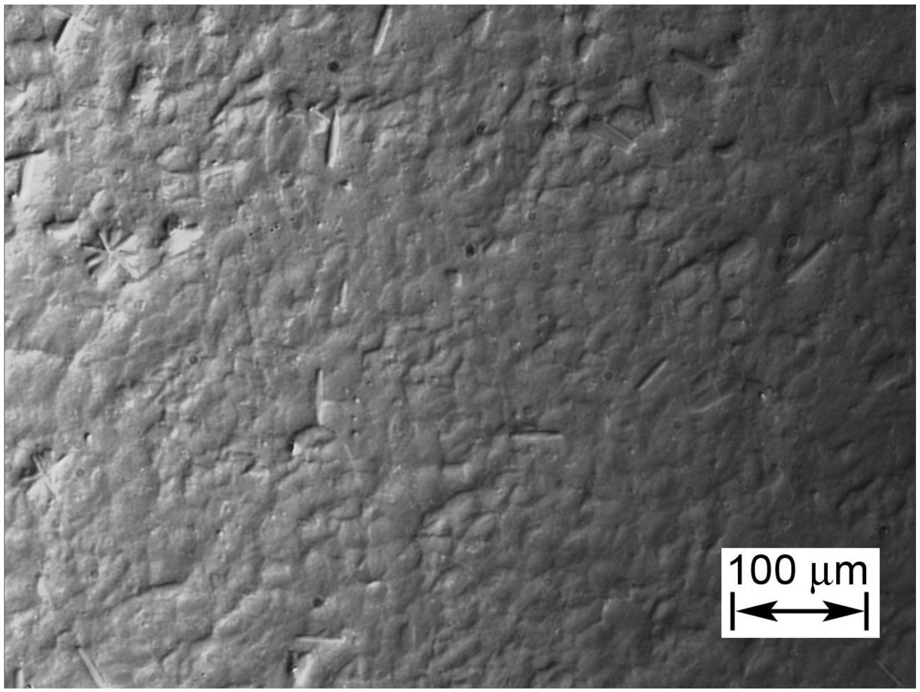
Two-stage processing to separate nucleation and growth phases.

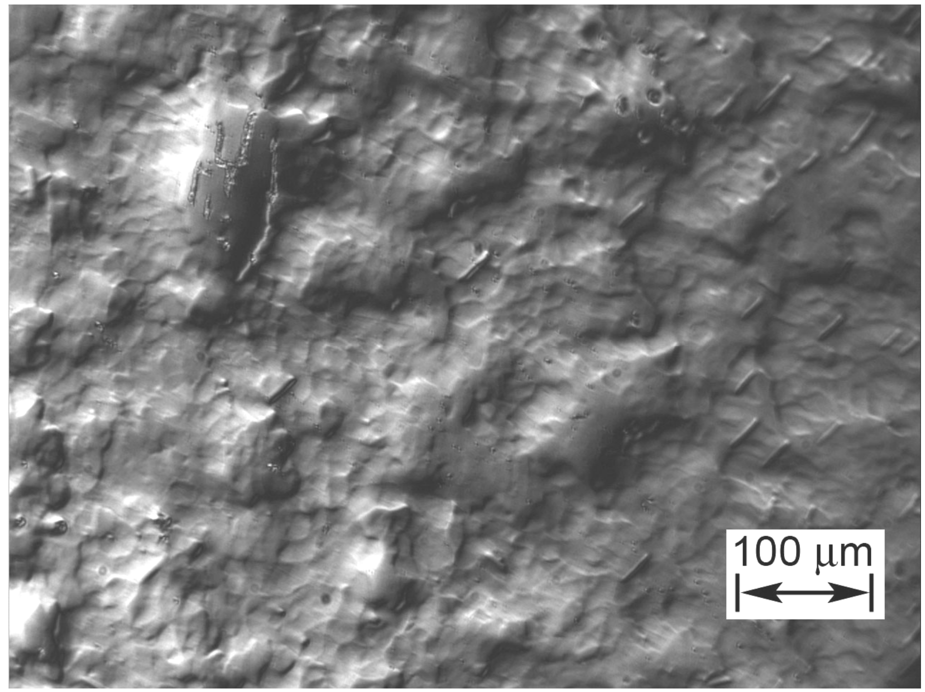
Growth rate $\propto P(H_2O)^{1/2}/P_{total}$



✓ After the nuclei cover the substrate, we reduce the pressure and increase the growth rate.

Reduction of the grain size by two-stage processing.



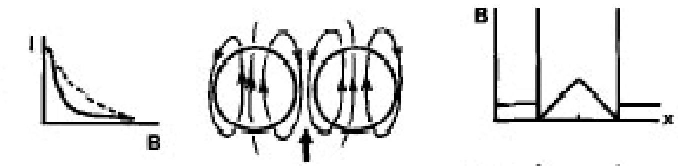


Two stage, small grain
J_c = 1.9 MA/cm^2

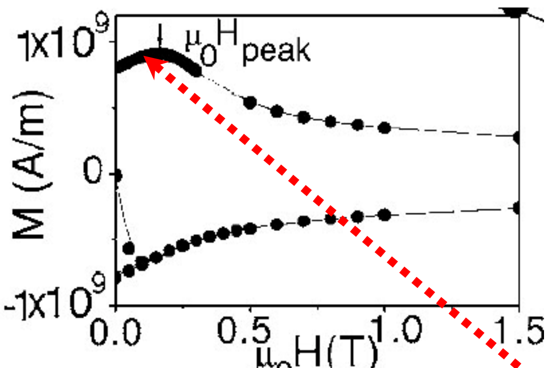
One stage, coarse grain
J_c = 1.1 MA/cm^2

✓ **Fast growth is essential for obtaining small-grain structure and high J_c.**

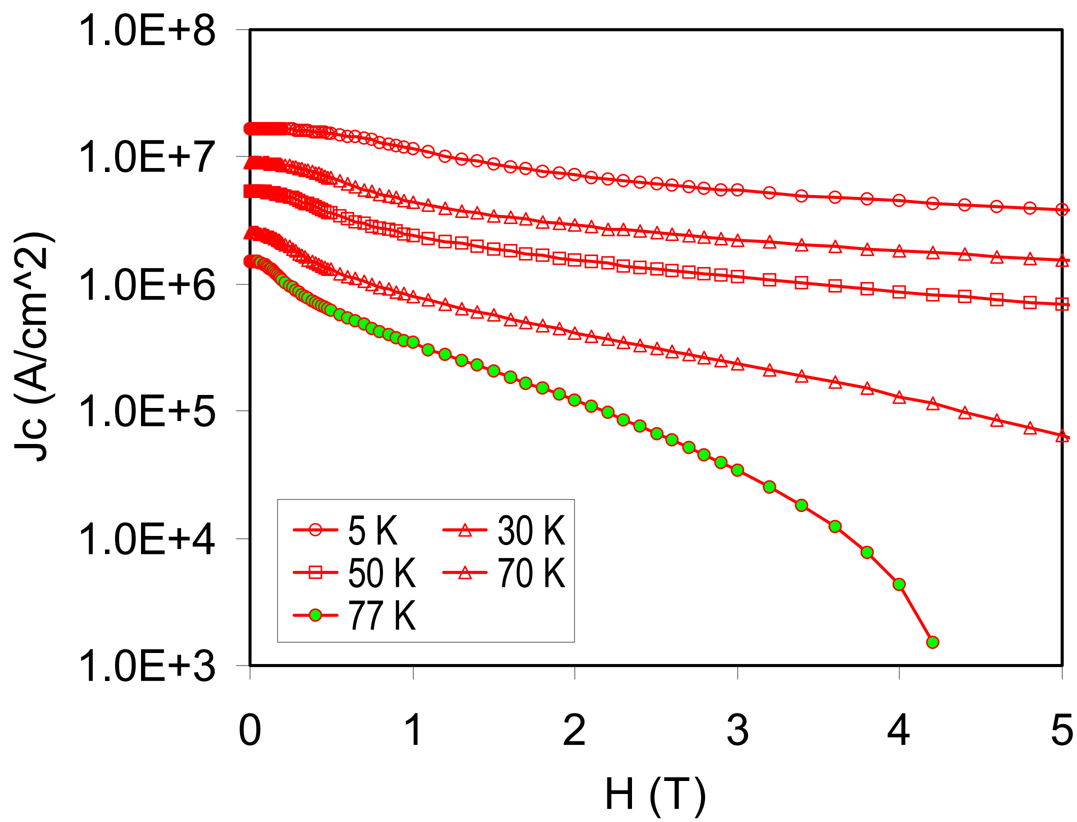
Why granularity degrades J_c? Evaluation of the grain connectivity.



J. E. Evetts and B.A. Glowacki, *Cryogenics*, 28, P. 641, (1988)



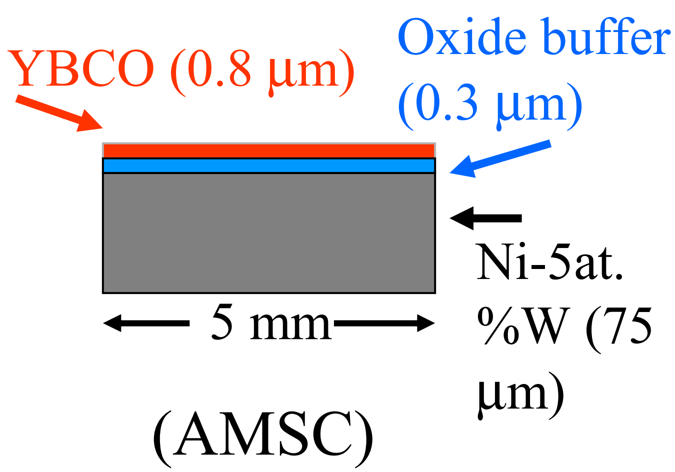
A. Palau et.al., *Phys Rev B*, 73, P. 132508 (2006)

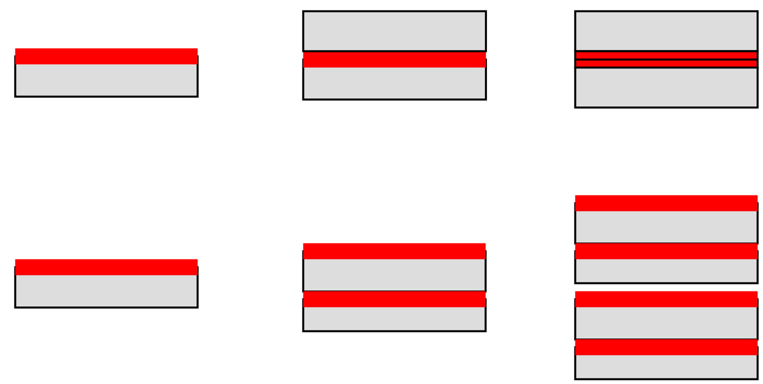


Magnetization measurements by Dr. Q.Li, BNL.

✓ **Absence of positive-field peak on m(H) return branch indicates that grains are well-connected .**

ac losses in stacks of YBCO films : Effects of Magnetic Substrate





(M. Suenaga and Qiag Li, APL, 88, P. 262501, (2006)

✓ac-losses in magnetic field *B* for a film with thickness *t*:

- Magnetic substrate: $\propto B^3/t$
- Non-magnetic substrate: $\propto B^4/t^3$.

✓Positive effect of magnetic substrate on ac-losses: reduction of field concentration near the edges ("magnetic mirror" effect).

Plans for FY2007

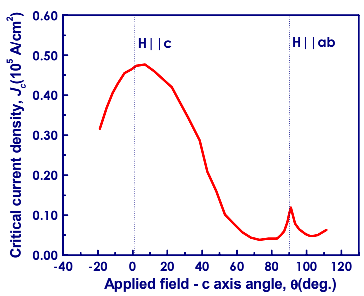
- Explore strategies for further improvements of the structure of YBCO layer:
  - Faster growth, lower processing temperature to reduce grains size.
  - Modification of the precursor layer to reduce the random nucleation.
- Extensive structural analysis of thick YBCO layers:
  - Quantitative relation between thickness of the near surface layer, average grain size and J_c.
  - Quantitative analysis of X-ray diffraction spectra. Role of other phases (cooperation with NIST).
- Continue microscopic study (TEM, RAMAN) of isolated nuclei.

Conclusions

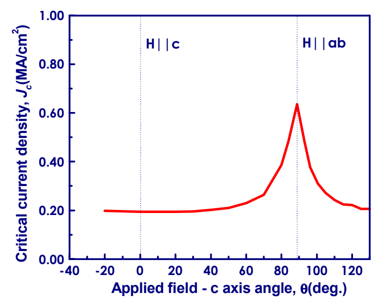
- We have demonstrated possibily of manufacturing 3 μm thick films with J_c = 1.9 MA/cm^2 and T_c = 92.5K on 4 cm RABITS tape.
- Two structural features characterize the film quality:
  - Thickness of near-surface randomly oriented layer YBCO
  - Size of c-axis oriented YBCO grains.
- Two nucleation phenomena pre-determine the structure:
  - Competition of near-surface random nucleation and epitaxial nucleation at the substrate.
  - Rate of activation of c-axis oriented islands during the growth stage.
- Thick films on technical buffers are prone to near-surface random nucleation.

Post-conclusion notes.

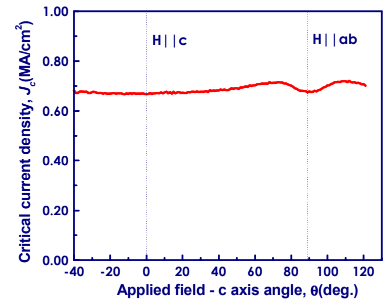
Critical current anisotropy in un-doped YBCO



Low S.
Flux-grown perfect crystals.
Point-like pinning by O^{-2} vacancies.



Intermediate S.
Atmospheric processing,
Pinning by extended defects (stacking faults etc.).



High S.
Sub-atmospheric processing,
Isotropic pinning.

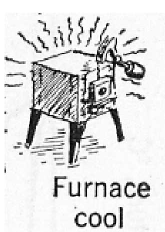
Decomposition — **$S = \Delta\mu/kT$ (supersaturation)** — **Growth**

Equilibrium

Is there a "critical rate"?

Metallurgic example: quenching of eutectoid (0.83%C) steel

	Furnace cool	Oil quench	Water quench
	Coarse pearlite	Very fine pearlite	Martensite
Tensile strength, psi	76,000	160,000	250,000
Yield strength, psi	20,000	80,000	
Hardness, Rockwell C	15	35	65
Elongation, per cent	12	5	low
Reduction of area, %	27	30	low



Post-conclusion notes.
Pinning in fast-processed samples.

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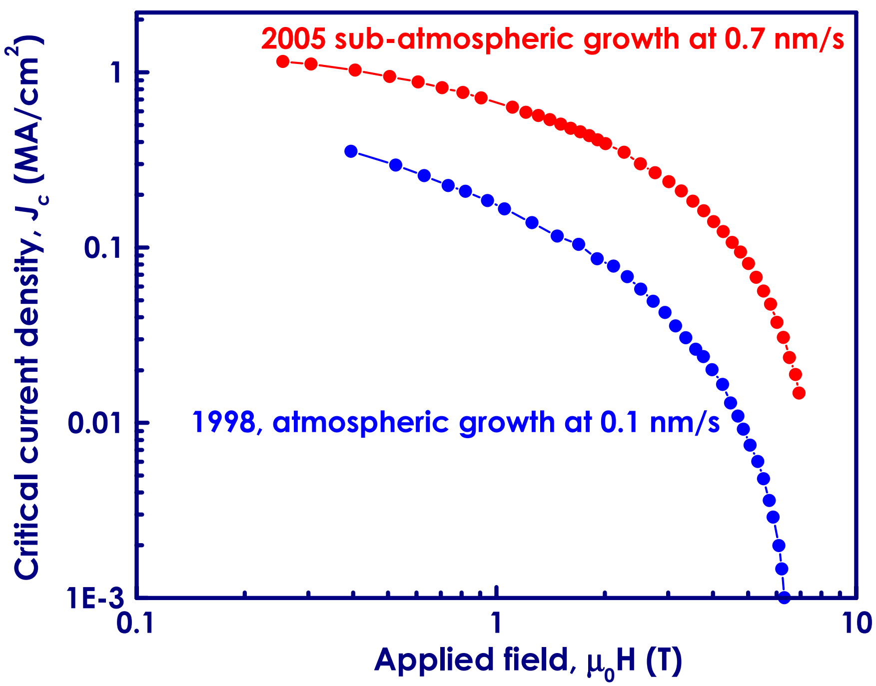
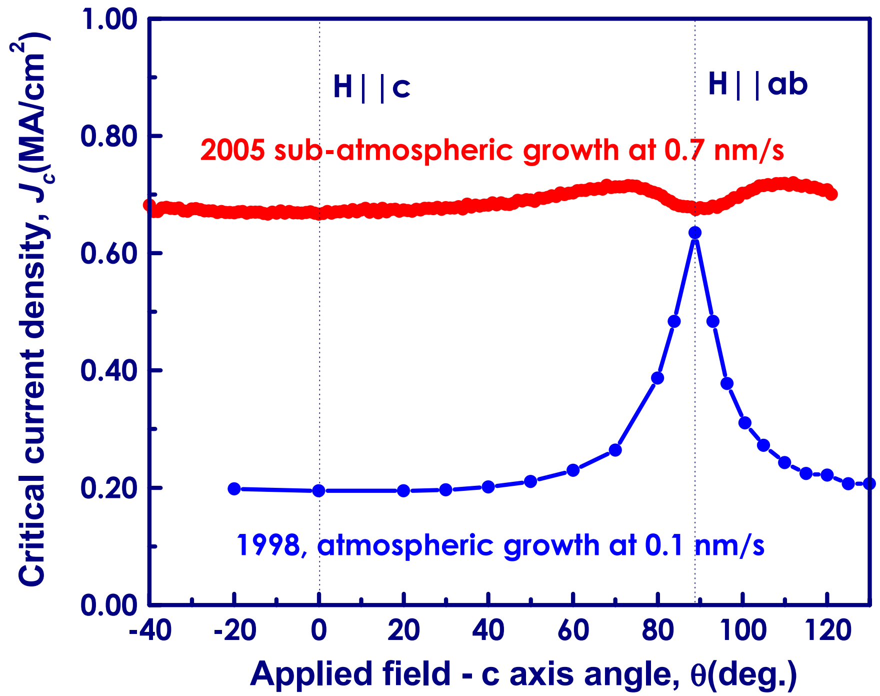
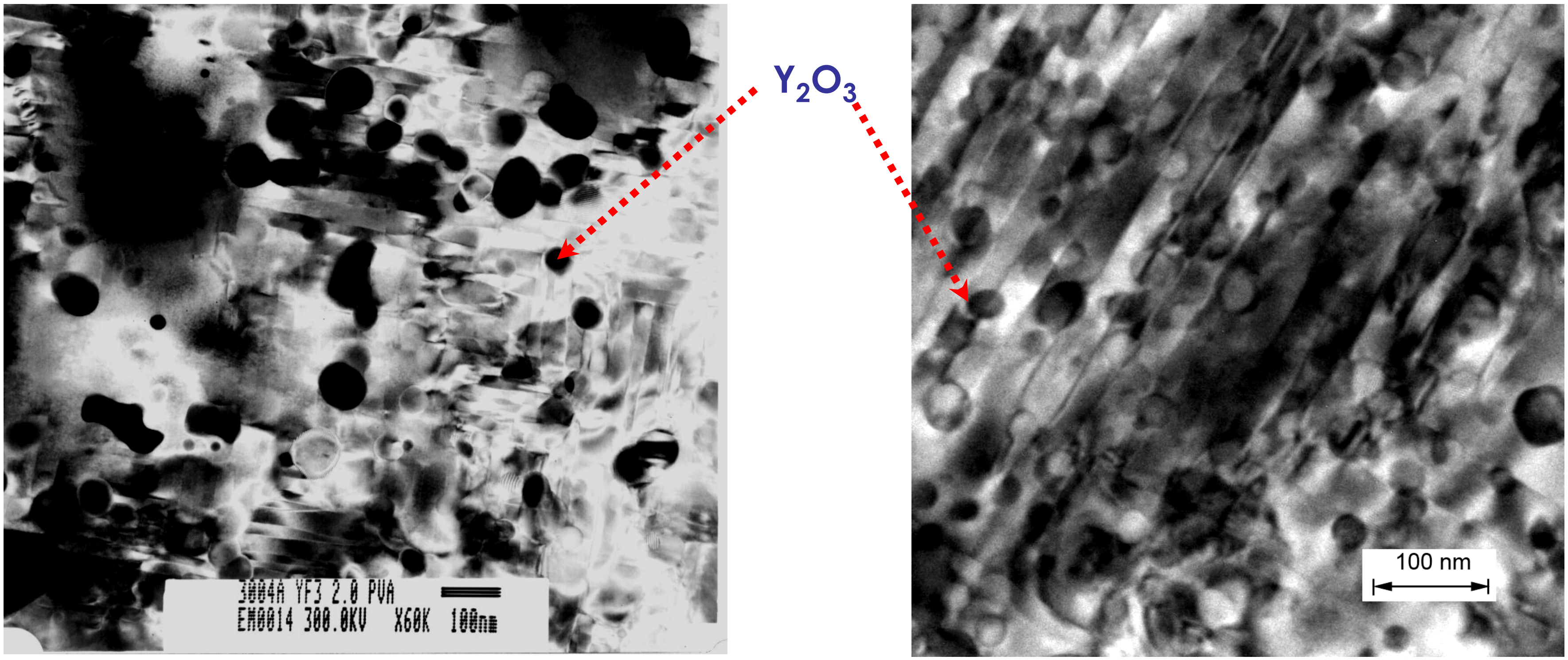
Growth temperature: 735 °C





✓ Fast growth and low growth temperature: two key ingredients for strong isotropic pinning.

Comparison: TEM plane view of atmospheric and sub-atmospheric processed 3 μm samples.



1998, atmospheric growth at 0.1 nm/s

2005 sub-atmospheric growth at 0.7 nm/s

- ✓ Density of obvious defects (precipitates) is about the same.
- ✓ Is there something we don't see in TEM?